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STUDIES IN CLIMATE DYNAMICS FOR ENVIRONMENTAL SECURITY: LARGE-SCALE OCEAN/ ATMOSPHERE INTERACTION RESULTING FROM VARIABLE HEAT TRANSFER AT THE EQUATOR

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Rand
SANTA MONICA, CA. 90406

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PREFACE

Meteorological studies suggest that technologically feasible operations might trigger substantial changes in the climate over broad regions of the globe. Depending on their character, location, and scale, these changes might be both deleterious and irreversible. If a foreign power were to bring about such perturbations either overtly or covertly, either maliciously or heedlessly, the results might be seriously detrimental to the security and welfare of this country. So that the United States may react rationally and effectively to any such actions, it is essential that we have the capability to: (1) evaluate all consequences of a variety of possible actions that might modify the climate, (2) detect trends in the global circulation that presage changes in the climate, either natural or artificial, and (3) determine, if possible, means to counter potentially deleterious climatic changes. Our possession of this capability would make incautious experimentation unnecessary, and would tend to deter malicious manipulation. To this end, the Advanced Research Projects Agency initiated a study of the dynamics of climate to evaluate the effect on climate of environmental perturbations. The present Memorandum is a technical contribution to this larger study.

Rand's position on climate and weather modification studies was asserted in its publications RM-3205-NSF and RM-5835-NSF. The approach to understanding the consequences of climate change must consist of many converging paths.

The present work, by Professor Bjerknes, has strong implications for our envisioned global models of atmospheric and oceanic circulation. It is a pilot study that takes note, first, of a regional ocean/atmosphere interaction in the equatorial Pacific, and second, of probably related remote effects across the face of the globe.

Professor Bjerknes is on the faculty of the Department of Meteorology at the University of California at Los Angeles, and is a consultant to The Rand Corporation.

SUMMARY

From the record of monthly sea and air temperature at Canton Island, 2°48'S, 171°43'W, November 1964 has been selected as typifying the arid conditions associated with anomalously cold equatorial water, and as representing a contrast to November 1965 with its near-maximum water temperature and abundant raintall. Air circulation along the equator also differs significantly, the cool November 1964 being characterized by uninterrupted easterlies from South America to eastern Indonesia with return flow in the upper half of the troposphere, whereas the corresponding circulation in November 1965 is confined to the eastern equatorial Pacific. In the western equatorial ocean, the weakening, or even elimination, of easterly wind stress, from 1964 to 1965, stops the upwelling, so as to permit the ocean surface to warm.

The large-scale feedback upon the atmosphere is seen to be: a general warming from November 1964 to November 1965 of the complete belt of the tropical troposphere with inherent strengthening of the upper tropospheric westerlies in both hemispheres. This underlines the importance for global climatic forecasting of monitoring, and if possible predicting, the atmosphere/ocean interaction in the equatorial belt.

ACKNOWLEDGMENTS

The present Memorandum is based on research supported in part by NSF (under Grant GA-3193) and in part by ARPA.

I also want to acknowledge the support from the Coast and Geodetic Survey, ESSA, Rockville, Maryland, for the acquisition of sea surface temperature records.

Moreover, I have been very fortunate in getting permission from Director General B. J. Mason of the British Meteorological Office to use the so far unpublished upper-air data from the equatorial station Gan in the Indian Ocean.

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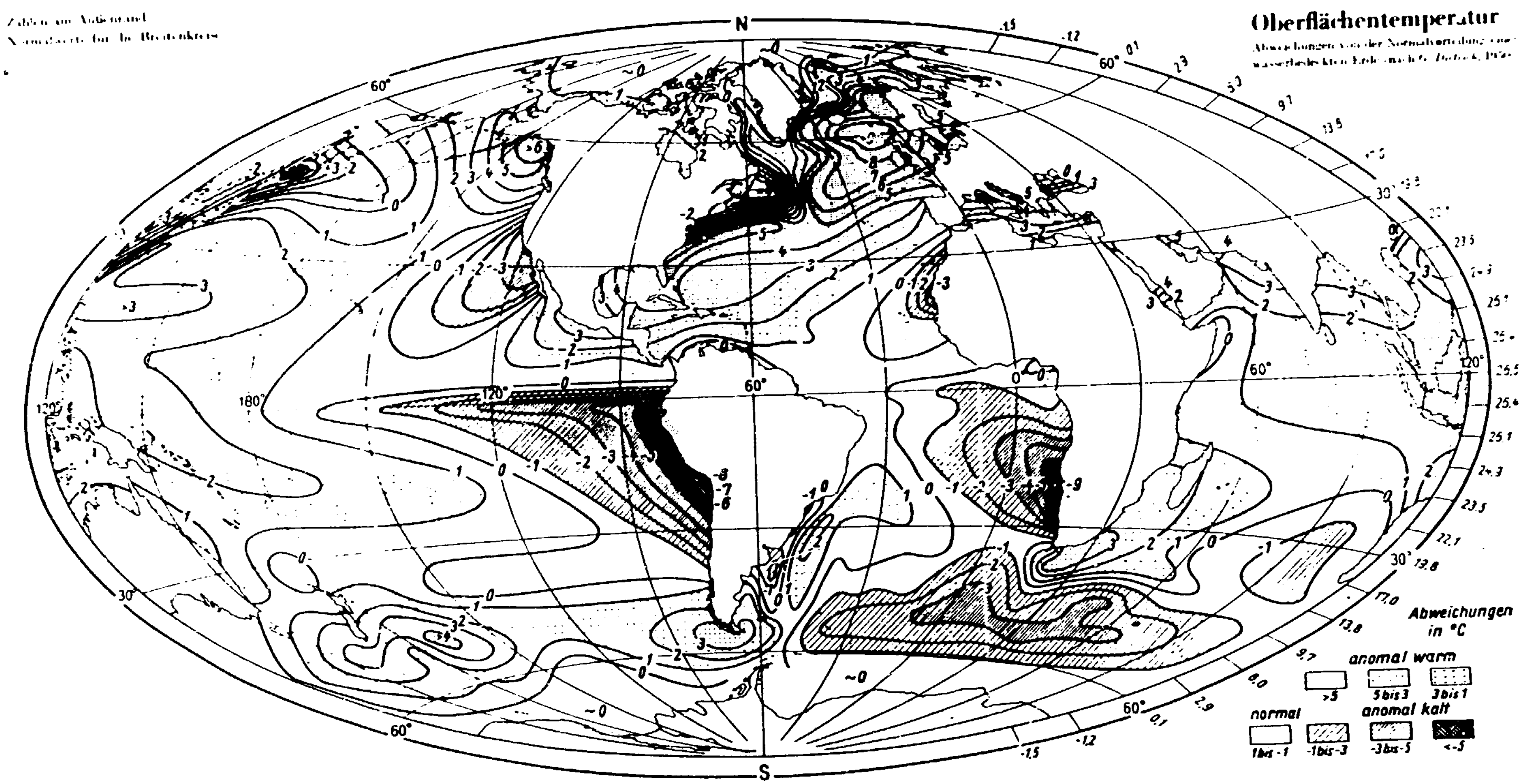
I. INTRODUCTION

Solar radiation passes through the atmosphere with but moderate absorption on its way, so it is delivered principally to the solid and liquid surfaces of the earth. The atmosphere obtains its heat supply mainly by the flux of long-wave radiation and the flux of turbulent heat (and latent heat) from below.

This report is concerned with the influence upon the atmospheric circulation of the long-term variability of the tropical heat supply -- especially that of the equatorial belt of the Pacific Ocean where the greatest area of highly variable sea-surface temperature is found. Austin (1960) showed that a major rise of mid-Pacific equatorial sea temperature that occurred in 1957 was not merely a superficial phenomenon but extended down to the thermocline and, therefore, must have been due to a temporary cessation of the normal equatorial upwelling. Following empirical studies by Ichiye and Petersen (1963), Bjerknes (1966, 1969), and Krueger and Gray (1969) have shown how the variations in equatorial sea-surface temperature regularly are accompanied by variations in the ocean-to-atmosphere heat flux which, in turn, have far-reaching consequences for the pattern and intensity of the atmospheric circulation. The present paper will elaborate some further aspects of this long-term large-scale ocean/atmosphere interaction.

Dietrich's (1957) global map of sea surface temperature is shown in Fig. 1. The mapped quantity is the long-term average deviation of sea surface temperature from its latitude average. The Pacific Ocean exhibits the largest area of subnormal temperature observed anywhere in the global tropical belt. On the average it extends from the South American coast along the equator to somewhat past the dateline, a distance more than a quarter of the circumference of the earth. The equatorial temperature deficiency of the surface water off South America is about 8°C and lessens gradually westward. The cause of the temperature deficiency is partly the cold water supplied by the Humboldt Current from southern sources, aided by upwelling along the Chilean and Peruvian coast. Even more important, though, is the upwelling along 10,000 km, more or less, of the Pacific equator.



1. Sea surface temperature represented as deviation from its average at each latitude. From Dietrich and Kalle (1957).

The upwelling in the open ocean along the equator is due to the prevailing easterly winds. In addition to the westward drift produced by these winds, a diverging Ekman drift is maintained, to the right north of the equator and to the left south of the equator, so as to pump upwelling water to the surface at the equator. So long as this process continues uninterruptedly, more and more upwelling water gathers at the surface and spreads sideways from the equator until a tongue of cold water is established as wide as that shown in Fig. 1.

The equatorial upwelling is to some extent self-amplifying because it keeps the eastern end of the equatorial belt several degrees colder than the western end. This east/west temperature contrast in the ocean causes the same sense of horizontal temperature gradient to prevail in the lower atmosphere. A thermal circulation in the atmosphere, with sinking air over the eastern part and rising air over the western part of the equatorial Pacific, therefore becomes a quasi-permanent link of the atmospheric circulation and converts potential energy into an increment of kinetic energy of the equatorial easterly winds. This, in turn, feeds back into increasing equatorial upwelling.

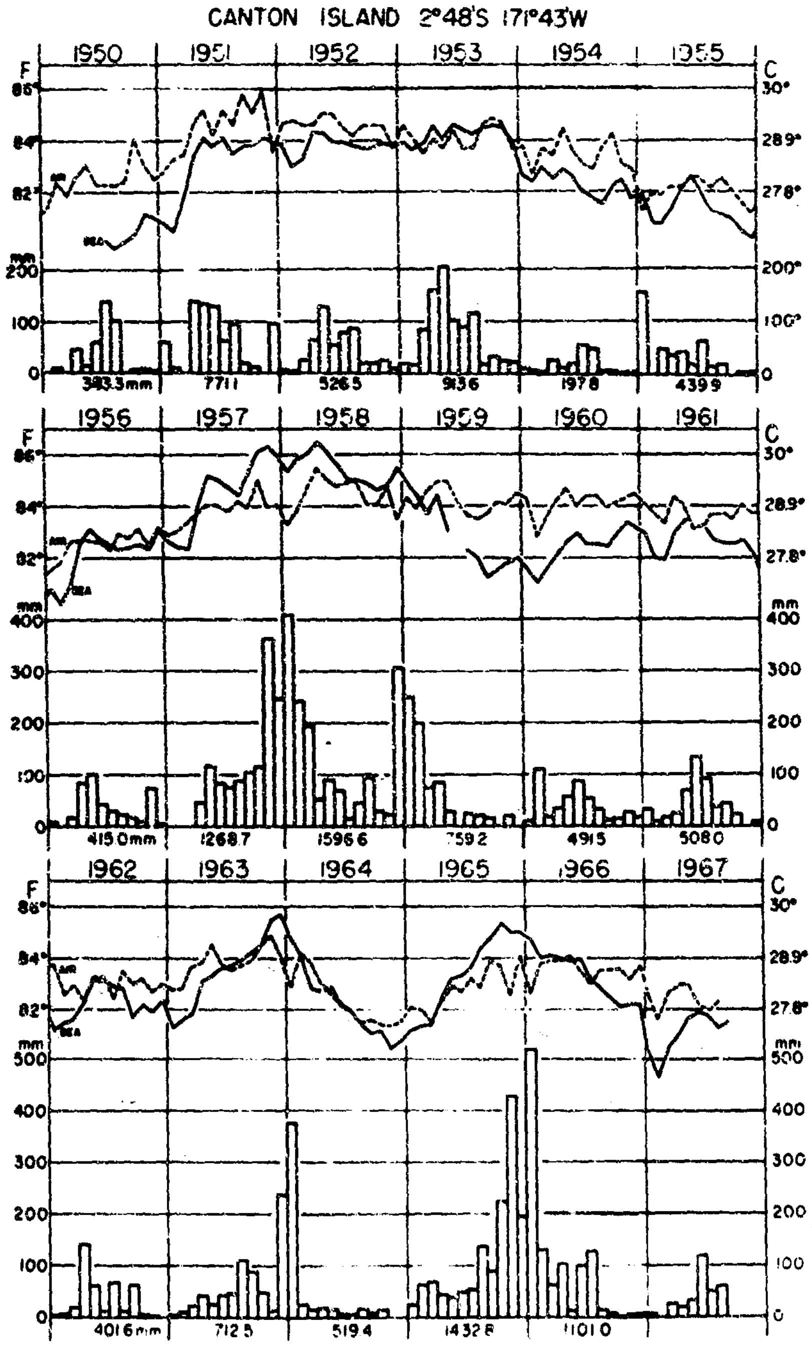
But the ocean/atmosphere interaction may also operate in the opposite sense. If, for instance, the equatorial easterlies are in the phase of decrease in their seasonal cycle, the upwelling will automatically decrease too. This lessens the oceanic east/west temperature contrast along the equator and deprives the easterly winds of the kinetic energy increment described above. Consequently, an accelerated decrease of the easterlies takes place which may ultimately lead to a calm, or to light variable winds, at the equator with the obvious result that the upwelling vanishes and warm water converges on the equator from the north and the south.

II. THE RECORD OF PACIFIC EQUATORIAL UPWELLING AND ITS FEEDBACK UPON THE ATMOSPHERE

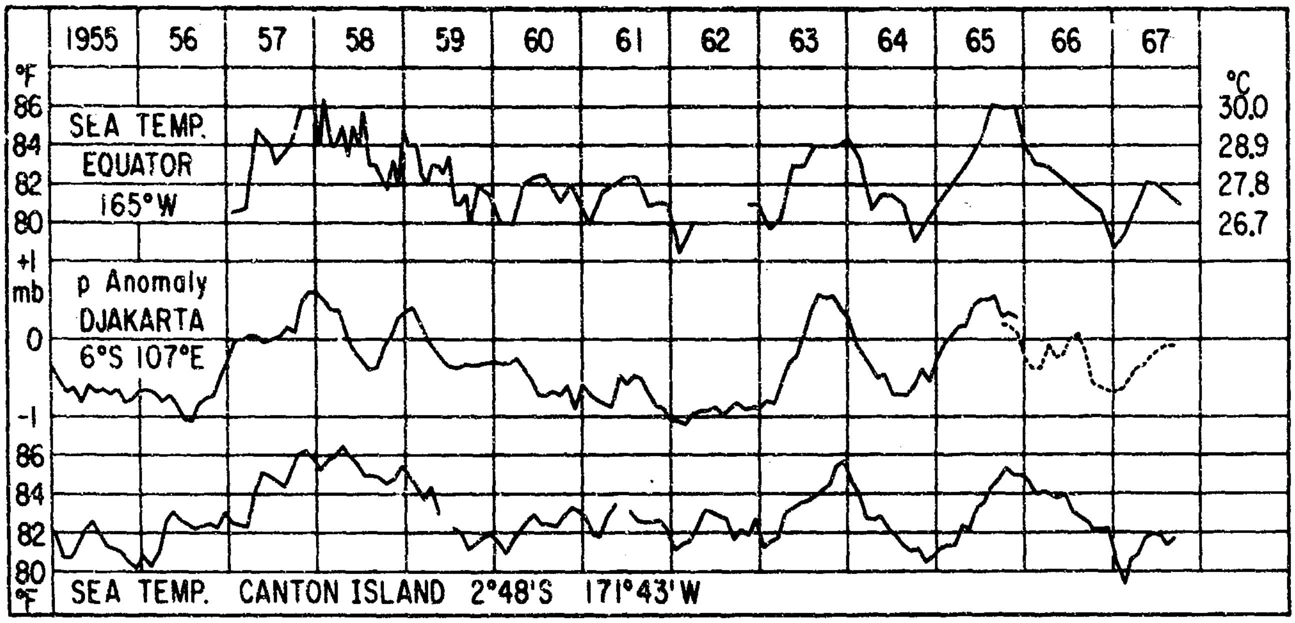
Canton Island, 2°48' S, 171°43' W, provides an interesting record of sea-temperature variations, which is shown for the period 1950 to 1967 in Fig. 2. Most of the time the waters originating from the equatorial upwelling reach to Canton Island and maintain there a relatively cool 27° to 28°C, but during several short periods the upwelling influence weakens enough, or ceases altogether, so as to permit monthly averaged values in the 29° to 30°C range to occur. During the 1960's a quasi-biennial temperature oscillation operated for a while, with maxima toward the end of 1963 and 1965 and minima in late 1962 and 1964 as well as in early 1967.

The Canton Island air temperature (dashed curve in Fig. 2) follows the major trends of the sea temperature, but deviates less from its average value. Hence, during periods of cold water the air is warmer than the sea, whereas in periods of warm water the air is colder than the sea. The latter condition leads to strong vertical convection in the atmosphere and, since moisture is readily available, also to rain (shown in the block diagram in Fig. 2). In November 1963 the sea temperature had just barely exceeded that of the air, and the heavy rain did not start until December. In 1965 the whole second half of the year had a sea temperature well in excess of the air temperature and abundant rain resulted. The periods of cold water can be seen to have had much less rain. These semiarid conditions are well represented by November 1962, 1964, and 1966.

The quasi-biennial oscillation of the 1960's can also be seen in the smoothed pressure time-series of Djakarta, Indonesia, as presented in Fig. 3 together with the sea surface temperature record of Canton Island and a supporting sea surface temperature curve derived from the logs of ships crossing the equator on their Honolulu to Samoa track. The fact that sea-level pressure at Djakarta changes in phase with mid-Pacific equatorial sea temperature, about one earth quadrant away, indicates that very long-distance teleconnections operate along the equatorial belt. Figure 3 shows that by selecting November as a test month



2. Time series 1950-1967 of monthly sea and air temperatures and monthly precipitation at Canton Island 2°48' S, 171° 43' W.



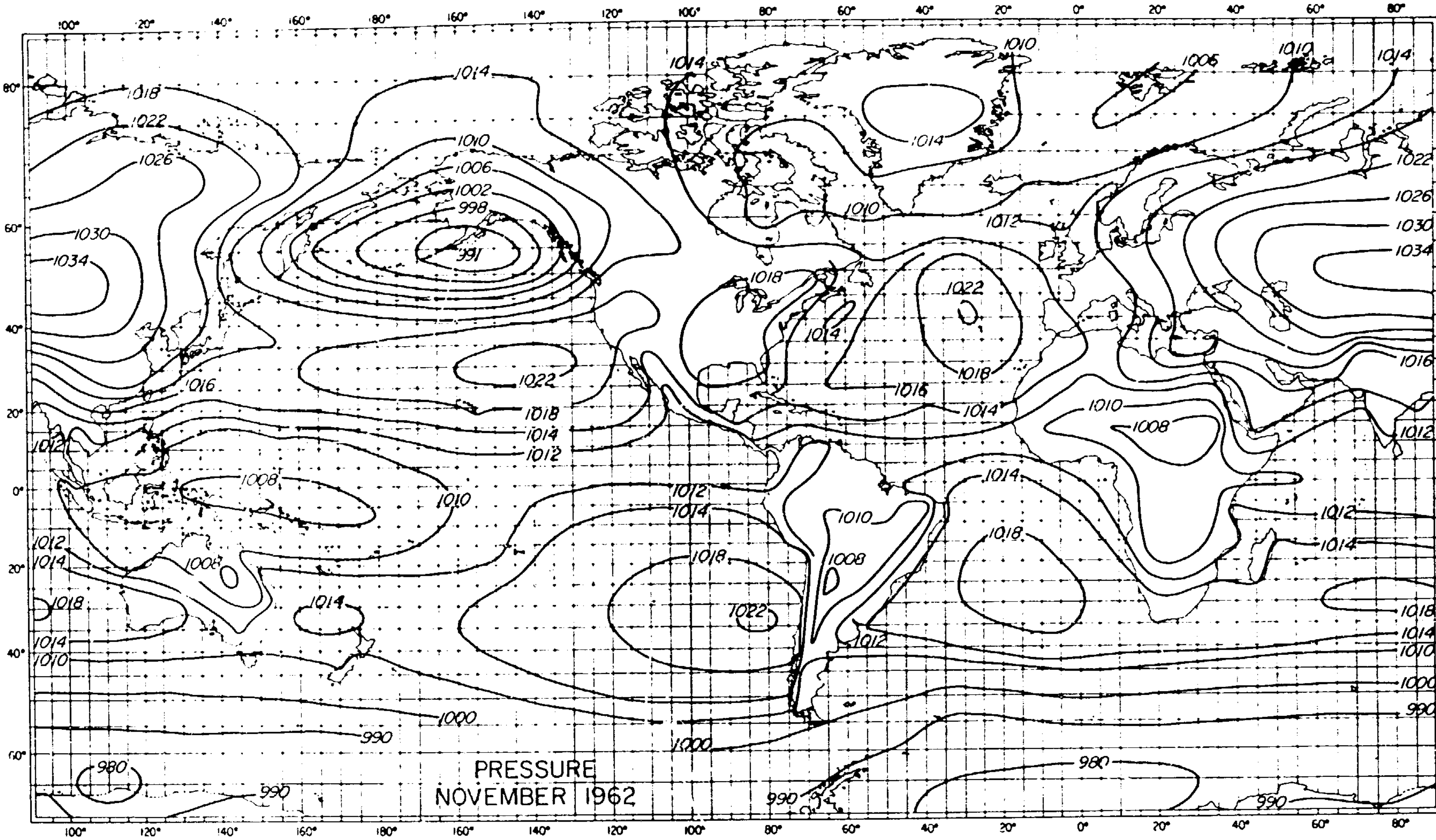
3. Walker's "Southern Oscillation" from 1955 to 1965 represented by 6-month overlapping averages of Djakarta monthly pressure anomalies (dashed curve continues with Singapore data). On same time scale: the monthly sea temperature at Canton Island (from Fig. 2) and the sea temperature at 165° W on the equator measured during individual ship crossings. The greater amount of short-period fluctuations shown in 1958-59 results merely from a greater frequency of ship crossings in those years.

in the following maps and diagrams we gain the advantage of testing the teleconnections at their phases of maximum response to the oscillating heating function at the equator.

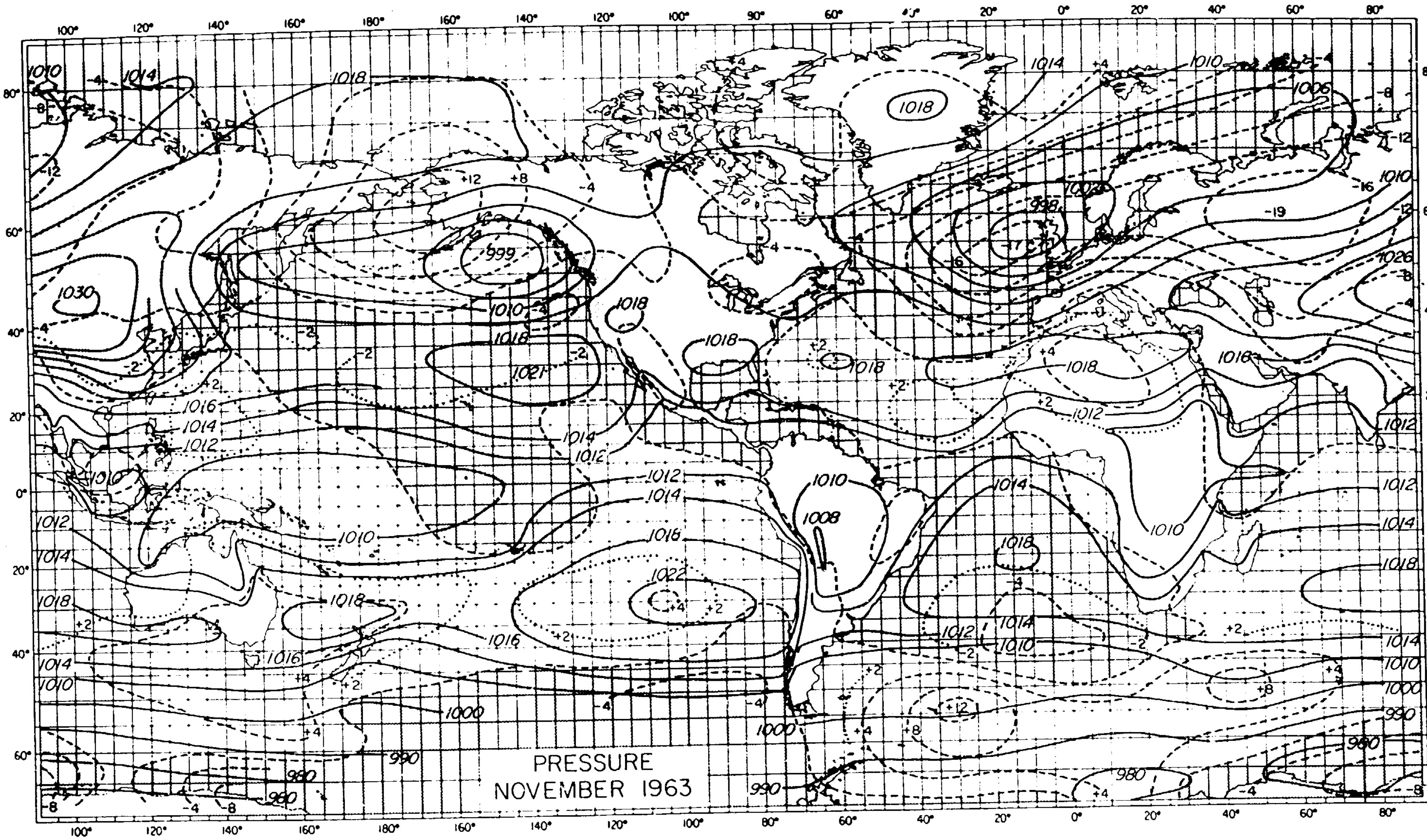
On the November sea-level pressure maps, Figs. 4 through 8, the biennial oscillation manifests itself in a west/east oscillation of the point of lowest pressure at the equator. In November 1962, 1964, and 1966 that point was near New Guinea, whereas in November 1963 and 1965 the low-pressure area extended farther eastward over the Pacific. A further important consequence of this oscillation can be seen in a stronger pressure gradient for the early winter monsoon over east Asia in 1962, 1964, and 1966 than in the years 1963 and 1965.

Figure 9 shows an example of how the equatorial wind pattern changes interannually, namely between November 1964, when the center of lowest pressure was at the western tip of New Guinea (130° E), and November 1965, when the pressure low was near Canton Island (170° W). The zonal wind component as a function of height is entered in Fig. 9 at six near-equatorial stations, from Africa in the west to South America in the east, and sketchy streamlines have been drawn. In November 1964, Pacific equatorial surface easterlies meet with equatorial surface westerlies from the Indian Ocean, and join into an updraft over the Indonesian low-pressure center, while in the upper troposphere the winds diverge from the updraft. Corresponding downdrafts are over the eastern equatorial Pacific and over the western Indian Ocean. I propose to designate the resulting Pacific and Indian Ocean circulation cells together "Walker Circulations" in memory of Sir Gilbert Walker, one-time director of the Indian meteorological service. He discovered what he called the "Southern Oscillation," which in my suggested interpretation is represented by the vacillation back and forth between the flow patterns exemplified in Fig. 9 by the two extreme types of November 1964 and 1965.

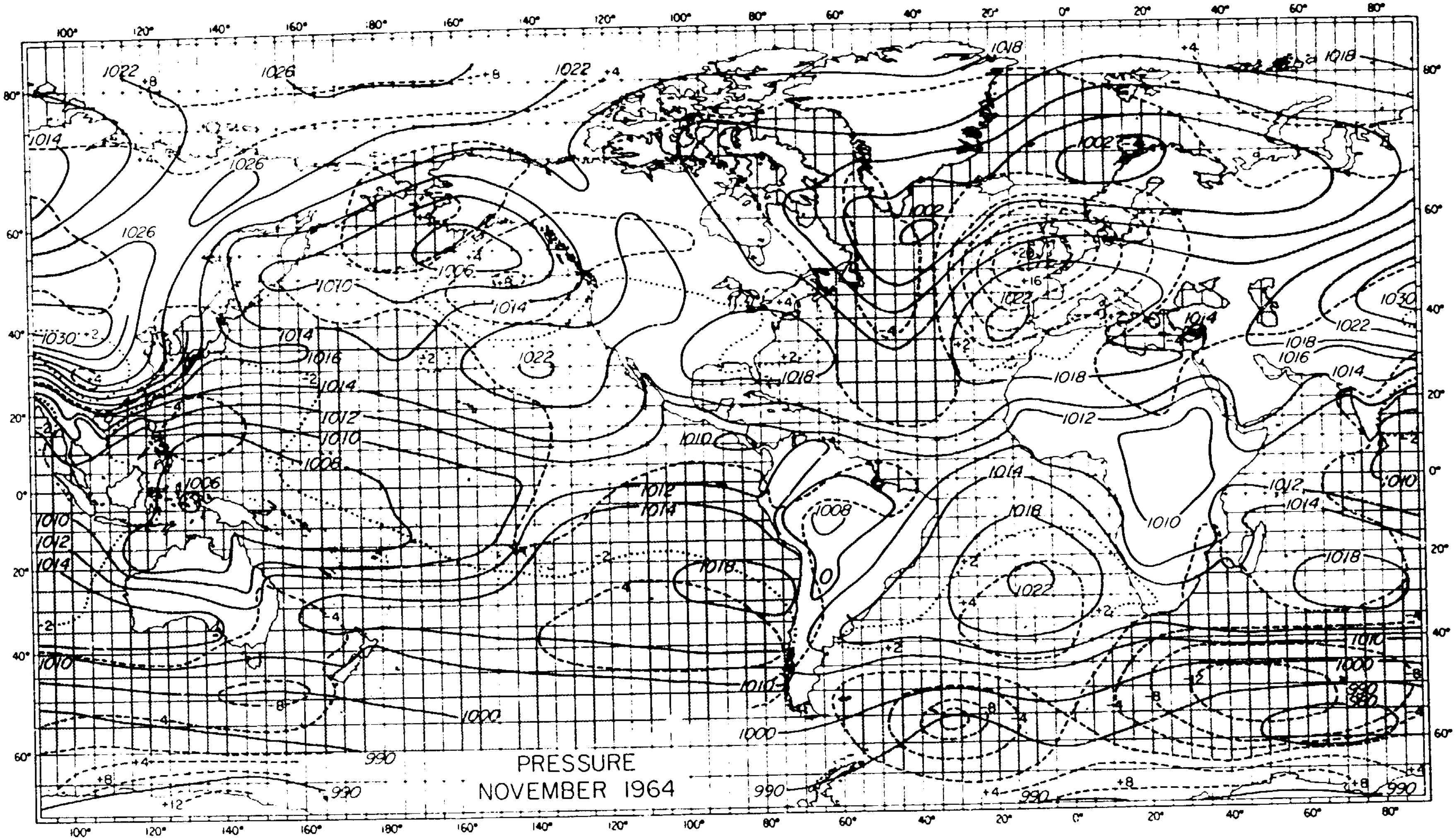
The November 1965 flow pattern maintains the Walker Circulation cells over the Indian Ocean and the Pacific Ocean, but that over the Pacific has shrunk back so as to occupy only the eastern half of the ocean. Ocean upwelling can be assumed to persist in that part although at Canton Island it has ceased. Both Canton Island and Singapore record



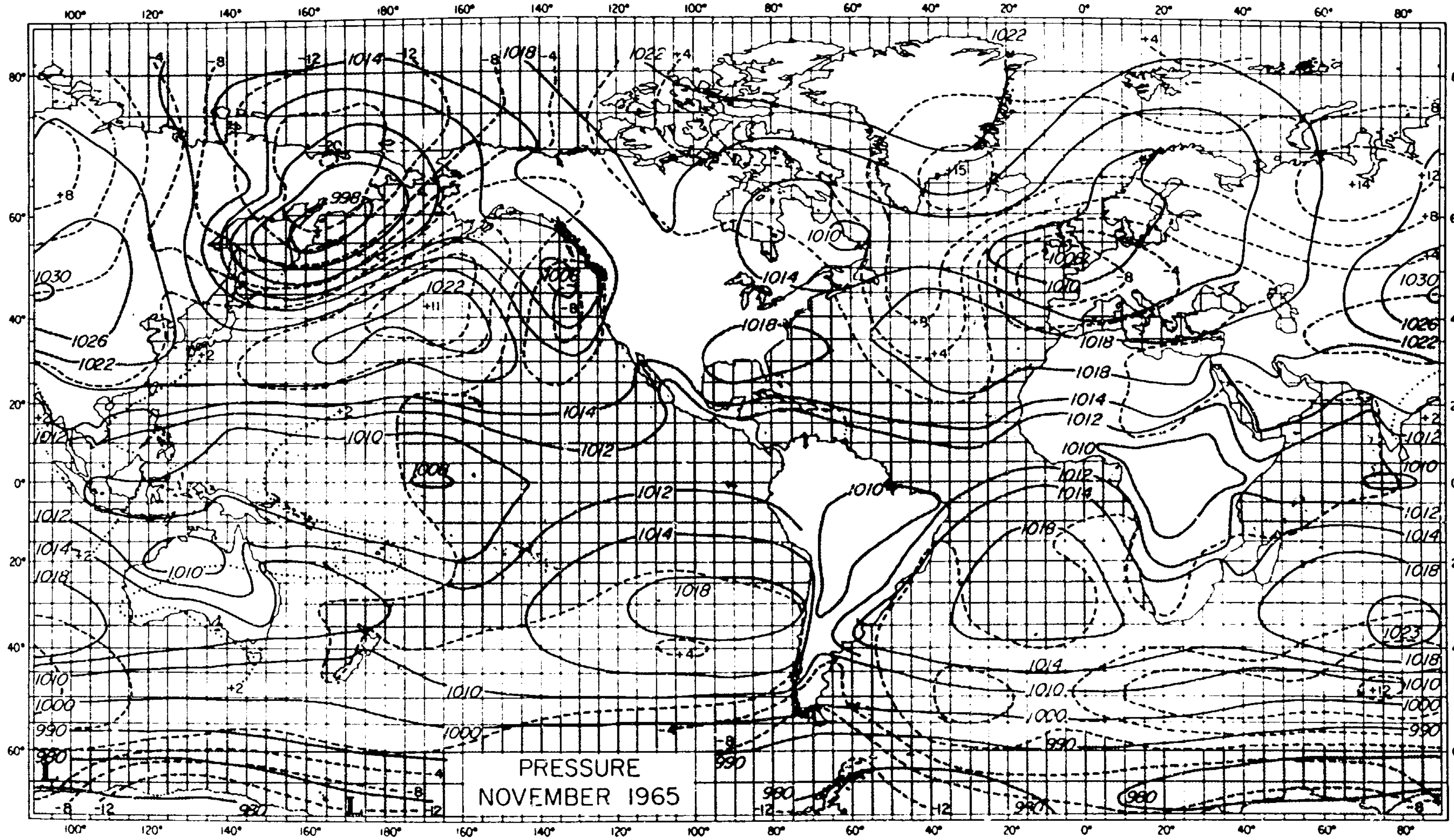
4. Sea-level pressure November 1962. (Dashed curves show pressure difference from preceding November. Shading marks areas of negative change.)



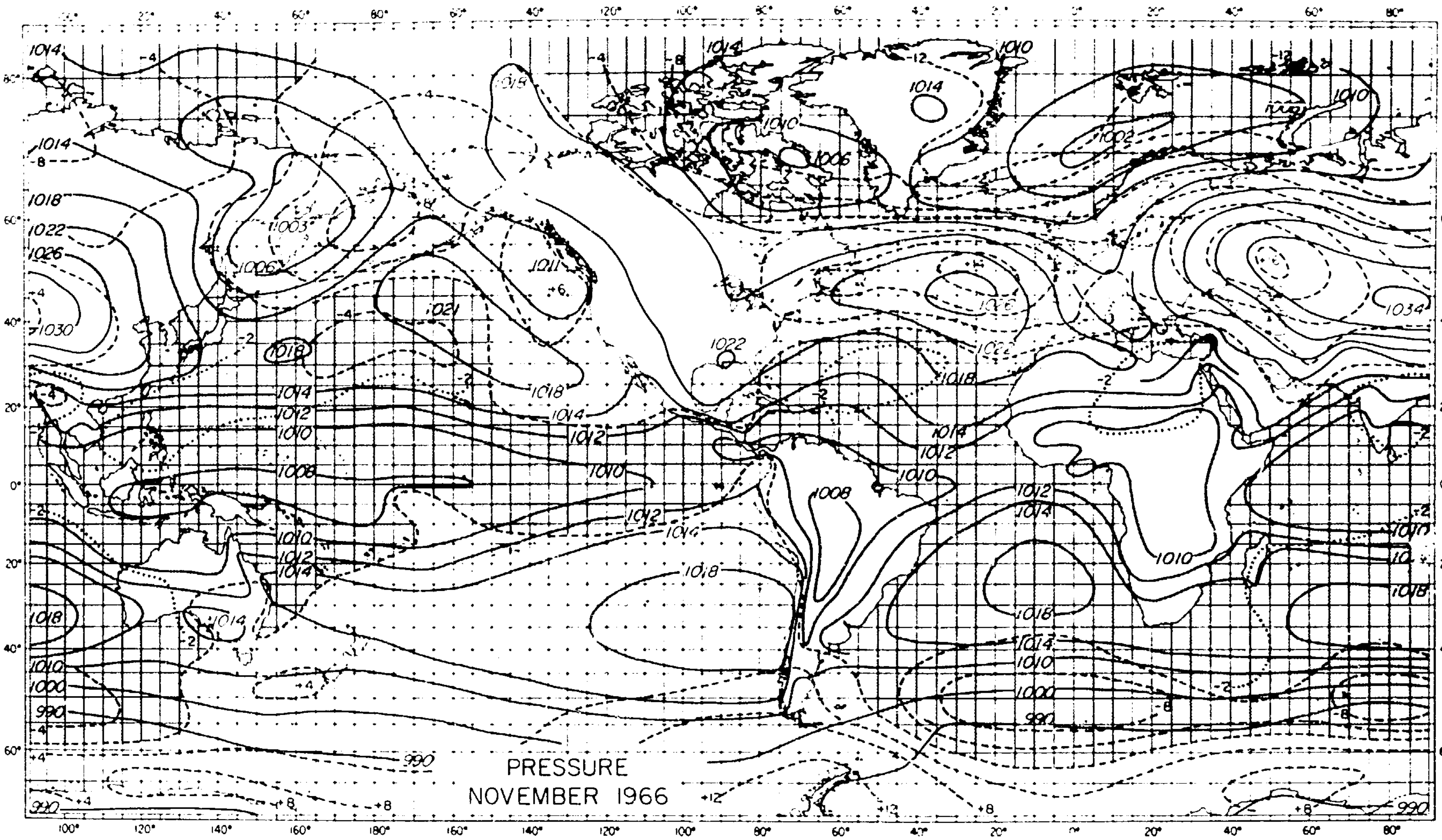
5. Sea-level pressure November 1963. (Dashed curves show pressure difference from preceding November. Shading marks areas of negative change.)



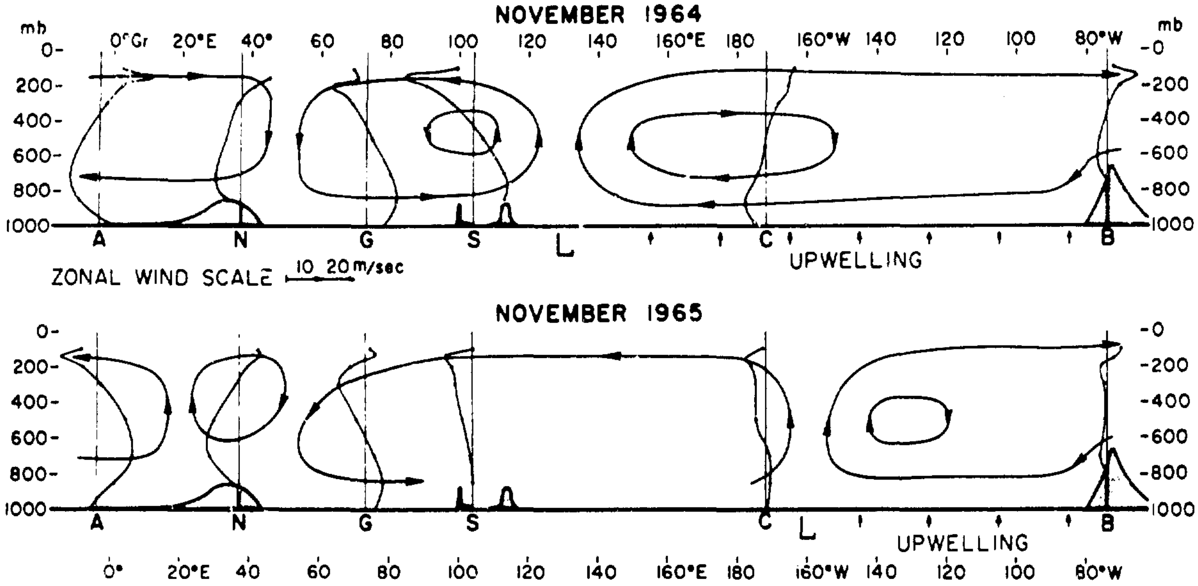
6. Sea-level pressure November 1964. (Dashed curves show pressure difference from preceding November. Shading marks areas of negative change.)



7. Sea-level pressure November 1965. (Dashed curves show pressure difference from preceding November. Shading marks areas of negative change.)



8. Sea-level pressure November 1966. (Dashed curves show pressure difference from preceding November. Shading marks areas of negative change.)



9. Quasi-equatorial profiles across the Indian and Pacific Oceans of average air flow in November 1964 and November 1965, based on ra-wind measurements at Abidjan 5°15' N, 3°56' W, Nairobi 1°18' S, 36°45' E, Gan 0°42' S, 73°10' E, Singapore 1°21' N, 103°54' E, Canton Island 2°48' S, 171°43' W, and Bogota 4°42' N, 74°9' W. Sense of vertical component, w, is inferred from the assumption that $\partial u/\partial x$ is numerically larger than $\partial v/\partial y$. L marks position of minimum sea-level pressure at the Pacific equator. Ocean upwelling extends from L eastward to the coast of South America.

quite light zonal wind components in the lower troposphere, and the whole stretch between those two stations can be assumed to have doldrum conditions without much superimposed large-scale zonal flow. With these slack winds, and no upwelling, the central and western equatorial Pacific must have warmed, and the resulting penetrative atmospheric convection must be operating under optimum conditions.

The two-dimensional streamlines in Fig. 9 should of course not be construed as representing strictly two-dimensional air trajecrories. For one thing, the Asian monsoons at the surface, and their upper counterflow, cut through the equatorial plane. Such transequatorial flow is, however, less pronounced in November than in midwinter and midsummer. Nevertheless, eddies of various scales are averaged into the large-scale flow patterns of Fig. 9 resulting in some air exchange between the Walker Circulations and the adjacent Hadley Circulations.*

The temperature soundings for November 1964 and 1965 in Fig. 10 and the maps in Figs. 11 and 12 are selected to illustrate some of these air-mass problems.

Canton Island in November 1964 has an average sounding with a stable layer between 850 mb and 700 mb. The air mass below the stable layer has travelled over long distances in contact with cool upwelling waters and before that has had a history of entering the Walker Circulation from the tradewinds of the southeast Pacific Hadley Circulation.

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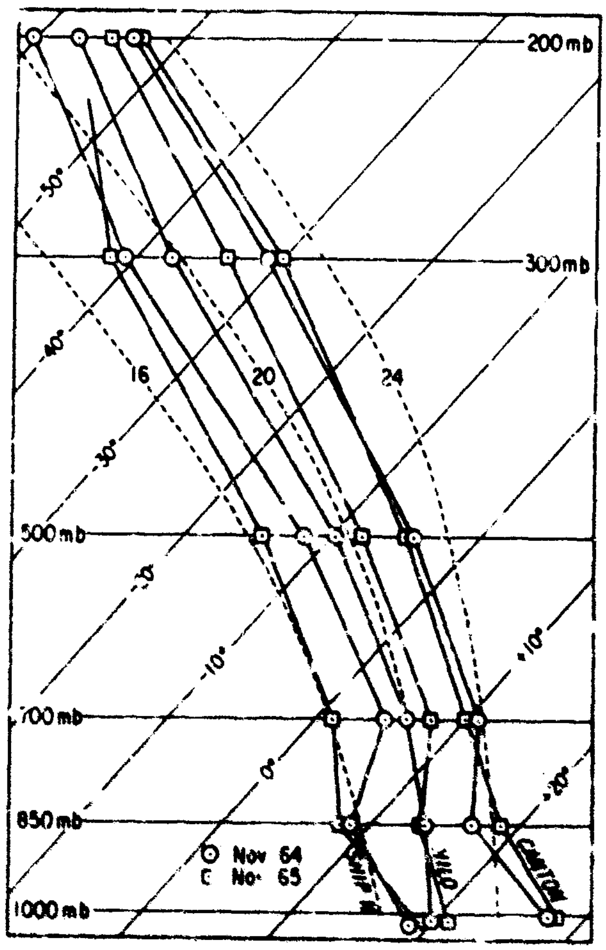
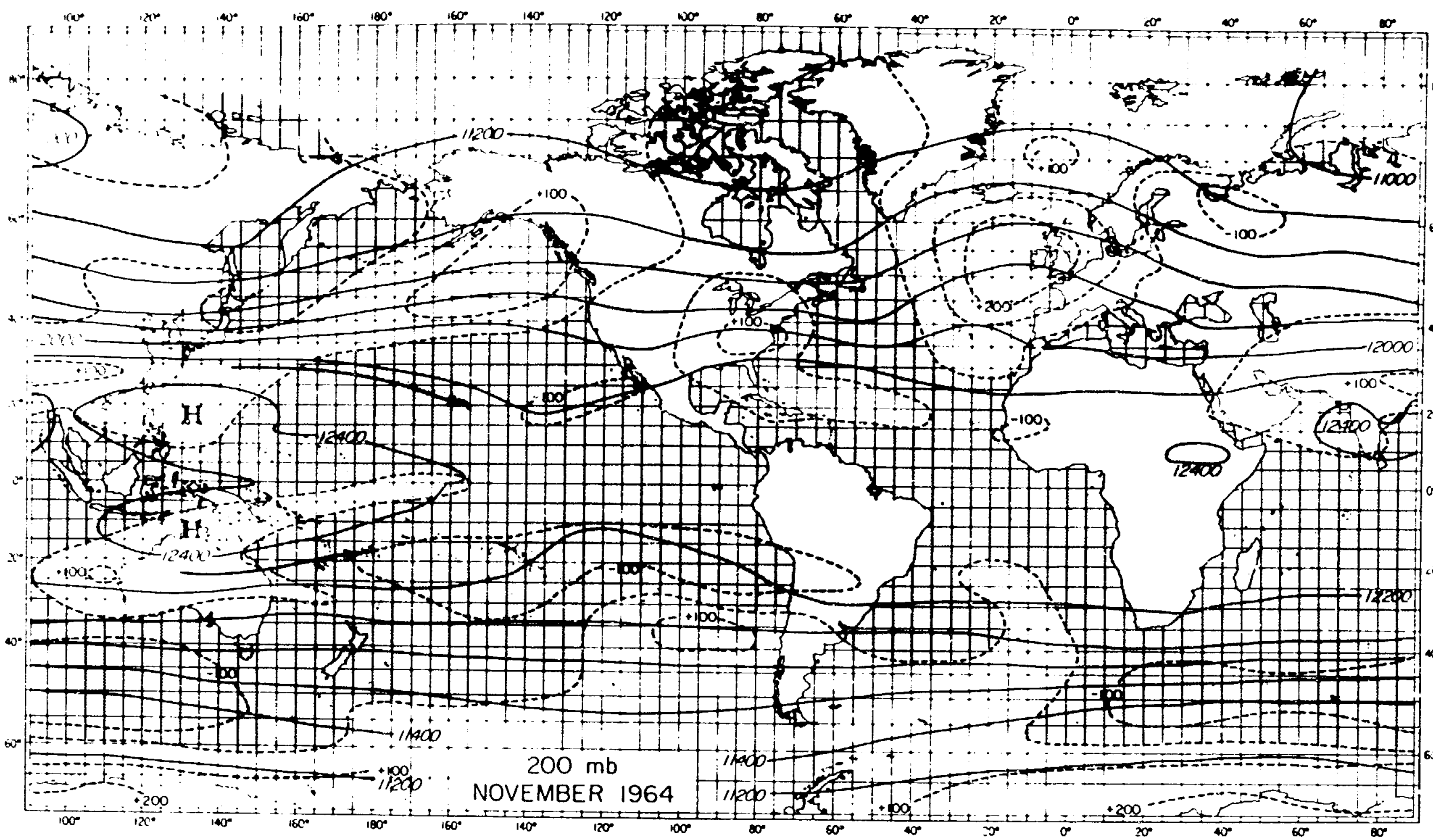
*The concept of the Hadley Circulations is based on the well-established fact that the tradewinds have a systematic component toward the equator and that upper winds must provide an approximately equal mass flow away from the equator. On a nonrotating earth the air orbits of the Hadley Circulations could simply have been contained in meridional planes, but on the rotating earth the orbits are tilting and have their highest point far west of their lowest point. In horizontal projection the Hadley Circulation air orbits are therefore anticyclonic and correspond to the several subtropical anticyclones always observed on the synoptic pressure maps. The axis of such a Hadley anticyclone is on the average to be found at 30° N or S at sea level. With increasing height the axis of each anticyclone is found farther west and closer to, but never quite reaching, the equator.

It follows from Fig. 9 that where the Walker Circulation maintains downward air motion the Hadley Circulations do not reach the equator. Where the air is rising the Walker and Hadley Circulations run parallel and air may be exchanged between them.

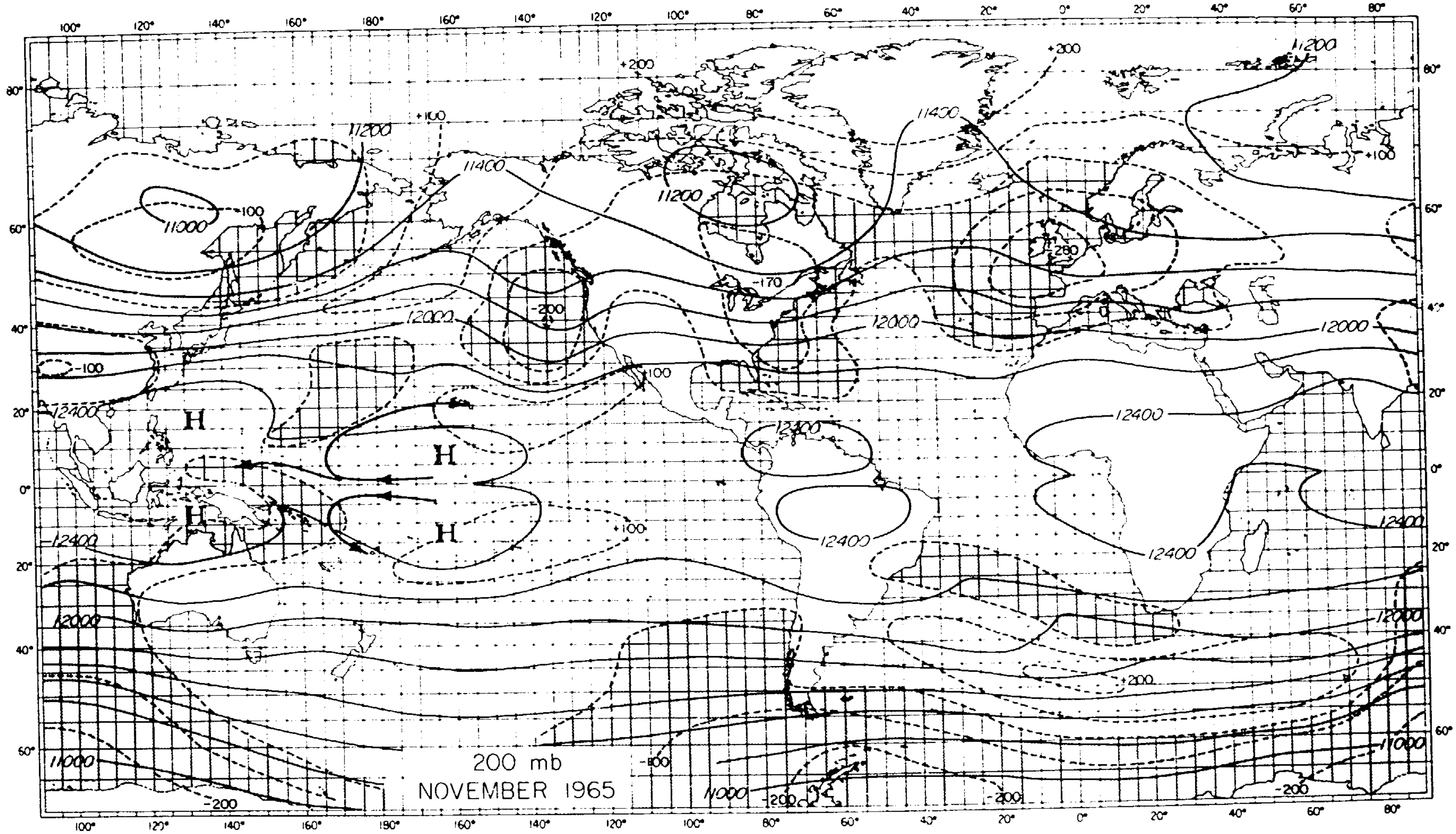


10. **Averaged temperature soundings for November 1964 and November 1965 at Canton Island 2°48' S, 171°43' W, Hilo 19°44' N, 155°4' W, and Ship N 30° N, 140° W. Dashed curves are saturation adiabats numbered with the temperature at their intersection with the 1000mb base.**

Canton Island shows between 850 mb and 700 mb a stable layer in November 1964 and no such stability in November 1965. Hilo, on the other hand, shows increasing low-tropospheric stability from 1964 to 1965 as the upper troposphere warms up with air advected from the equator. Ship N soundings, north of intensifying westerly jet stream, have cooled off from 1964 to 1965 while those of Hilo have warmed up.



11. November 1964 200mb heights (gpm). Dashed curves contour the changes in 200mb heights from November 1963. Shading marks areas of negative change.



12. November 1965 200mb heights (gpm). Dashed curves contour the changes in 200mb heights from November 1964. Shading marks areas of negative change.

The Canton Island air above the stable layer is very dry, indicative of a history of sinking motion within the eastern part of the Pacific Walker Circulation. The upper-tropospheric air above 500 mb originates from the updraft over Indonesia at the western end of the Pacific Walker Circulation; and between 500 mb and sea level the air is heading toward that updraft, gradually warming up from below while travelling toward warmer ocean.

By November 1965 the updraft has been shifted to the mid-Pacific, and the Canton Island sounding for that month illustrates the thermal structure of the updraft air column. The stable layer has disappeared, and conditional instability extends from sea level through the major portion of the troposphere. That means that rising cloud towers, or meso-scale clusters of such clouds, can remain warmer than the environment and therefore accelerate upward by buoyancy. At the top of the updraft the air can either return eastward and remain in the Pacific Walker Circulation, or go westward to the Walker Circulation cell above the Indian Ocean, or part of it may branch off into the upper part of the Hadley Circulations of the northern and southern hemispheres. The latter alternative seems to have been represented to a considerable extent in November 1965 as indicated by the big rise of upper-tropospheric temperature from 1964 to 1965 in the soundings from Hilo, Hawaii, at 20° N, shown in Fig. 10 (and likewise in subtropical soundings south of the equator, not entered in Fig. 10).

Figure 12 charts the possible trajectories in November 1965 for the air having ascended to the 200mb level and then having branched off into the anticyclonic Hadley Circulations of either hemisphere, whereas Fig. 11 shows the antecedent conditions in November 1964 when no such branching took place over the mid-Pacific. Both Figs. 11 and 12 show the additional symmetrical western pair of 200mb anticyclones centered, respectively, near the Philippines and over northern Australia. Those upper high-pressure systems are associated with the semipermanent Hadley Circulations that receive their heat supply from the permanently warm Indonesian waters and land masses, whereas the corresponding mid-Pacific upper anticyclones owe their existence to the Hadley Circulations developing in 1965 supported by the enhanced heat supply made available over the equatorial waters of the west and middle Pacific.

But the tropical warming, and the inherent raising of the 200mb isobaric surface from 1964 to 1965, extended much farther; actually it went around the globe.* In Figs. 11 and 12 the change of the 200mb height from one year to the next is contoured by dashed isolines at 100-gpm intervals, and the areas of negative change from the preceding November are marked by shading. The grand pattern emerges of a globe-circling lowering of the 200mb surface over the tropical belt from November 1963 to November 1964 and a rising from November 1964 to November 1965, just in phase with the cooling and subsequent warming of the Pacific equatorial waters shown by Canton Island in Fig. 2.

It is suggested that most of the tropical tropospheric heating trend from November 1964 to November 1965 is initiated by the increased ocean-to-atmosphere heat and latent heat supply in the updraft region between the two Walker Circulations, first over Indonesia in late 1964 and later spreading over a much larger area of the western and central equatorial Pacific as the water temperatures there increased. Intensifying joint upward volume transport of the two Walker Circulations apparently calls for immediate increase of the down-drafts over the east Pacific and the western Indian Ocean, where, then, the thermal equilibrium between adiabatic heating of sinking air and radiative heat loss gets disturbed in favor of the adiabatic heating. In this way the surplus heating in the updraft (mainly by the heat of condensation) quickly reaches about two-thirds of the tropical circumference.

The remaining one-third, extending from the Andes to equatorial Africa also warmed up in phase with the rest of the tropical belt. It is possible that the tropospheric warming in that sector may have arisen in the equatorial Atlantic in analogous fashion as over the Pacific, but the Atlantic variability of sea temperature at the equator is known to be smaller and confined to a much smaller area than in the Pacific, so it must be of secondary importance in shaping the glob... atmospheric circulation. Inter-annual variability of heat supply from equatorial Brazil and equatorial Africa may therefore have been more important but

*As demonstrated also for the subsequent equatorial cooling period from January 1966 to January 1967, by Krueger and Gray (1969).

cannot be assessed without further research. The final answer may simply be that a tropospheric warming, such as that from 1964 to 1965 involving as much as two-thirds of the tropical belt, also must spread to the remaining one-third because the atmosphere in an equatorial profile cannot be very baroclinic.

The influence of the 1964 to 1965 tropical heating trend upon the northward adjacent part of the atmosphere can also be judged from the 200mb map of November 1965 (Fig. 12). The shaded area, extending from the northeastern Pacific, across North America and the Atlantic, to Europe, shows 200mb heights lower than in November 1964. This indicates a strengthening of the westerly winds along the southern edge of the shaded area, hence within reach of the Hadley Circulations over a 180° longitude stretch from about 150° W to 30° E. This is what should be expected from the intensification of the Hadley Circulations in the atmosphere over the warmer-than-normal tropical belt.

The Hadley Circulations feed air of high angular momentum to the subtropical westerly jet stream while feeding air of low angular momentum in lower layers to the tropical easterlies. The 200mb map of November 1965 shows more activity of that kind than that of November 1964, particularly, as described, over the western Pacific, but possibly also over the less well-monitored parts of the tropical belt over South America and Africa.

The stationary waves in the middle latitude upper westerlies were also rather different on the two November maps. In November 1964 only two major troughs stood out: (1) over east Asia connected with the activity of the north Pacific polar front between the cold continent and the warm Kuroshio and (2) over Newfoundland related to the north Atlantic polar front between the cold continent and the warm Gulf Stream. In November 1965 the abnormal warming of the equatorial mid-Pacific has produced the Hadley anticyclone south of Hawaii, and downwind repercussions from it in the westerlies maintain the three troughs: (1) off the west coast of North America, (2) over eastern North America, and (3) over western Europe.

The November 1965 polar-front activity is consequently affected in a different way over the two northern oceans. The Pacific polar front

disturbances, under the influence of pressure build-up of the mid-Pacific anticyclone, move farther northward than normal and maintain a deep low over the Bering Sea, 40° farther west and 5° farther north than the more normal position of the Aleutian Low shown in November 1964. Meanwhile, the Atlantic polar-front disturbances follow in 1965 the westerly upper-tropospheric jet stream from North America to the Mediterranean. The resulting asymmetry about the polar axis makes the polar high move to Greenland and the low normally near Iceland is displaced to the British Isles.

All these large-scale re-arrangements within the atmosphere seem to be logical teleconnections of the increase in the heat supply from the equatorial Pacific Ocean. It may be added that even the Arctic Ocean felt the impact by way of the southeasterly winds in the Beaufort Sea, alleviating the ice blockade of the Alaskan and the arctic Canadian coasts; and the northeasterly winds in the Atlantic sector, worsening the ice blockade of eastern Greenland and northern Iceland.

III. SUMMATION

The main subject matter of this report -- the large-scale atmospheric teleconnections emanating from the equatorial Pacific -- is, of course, not adequately covered by dealing with just one case illustrated by the difference between November 1964 and November 1965. Many more cases in different years and seasons should be analyzed to strengthen and to expand the initial empirical findings presented here, and they should be tested also by dynamic simulation with electronic computers powerful enough to treat joint global models of oceans and atmosphere.

On the way to that distant goal many more global data must be gathered and studied within the grand cooperating schemes of the International Decade of Ocean Exploration (IDOE) and the Global Atmospheric Research Project (GARP).

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10. ABSTRACT

A brief investigation of long-term variability of the tropical heat supply of the Pacific Ocean and its influence on the atmospheric circulation. From the record of monthly sea and air temperature at Canton Island, 2 deg 48 min S, 171 deg 43 min W, November 1964 is selected as typifying the arid conditions associated with anomalously cold equatorial water, and as representing a contrast to November 1965 with its near-maximum water temperature and abundant rainfall. Air circulation also differs significantly here. The large scale effect on the atmosphere from November 1964 to November 1965 is described as a general warming of the complete belt of the tropical troposphere with inherent strengthening of the upper tropospheric westerlies in both hemispheres. This emphasizes the need for monitoring and predicting the atmosphere/ocean interaction in the equatorial belt as a contribution to a global climatic model.

11. KEY WORDS

Oceanography
Atmosphere
Meteorology
Heat Transfer
Climate